Title

OVERVIEW OF HEAVY ION FUSION PROGRAM IN U.S.A

Author

Keefe, Denis

Publication Date

1978-02-01

Presented at the International Atomic
Energy Agency Technical Committee Meeting
on Progress in Inertial Confinement Fusion,
San Francisco, CA, February 1 - 6, 1978

LBL-7519 c.2

OVERVIEW OF HEAVY ION FUSION PROGRAM IN U.S.A.

Denis Keefe

February 2, 1978

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

Presented at International Atomic Energy
Agency Technical Committee Meeting on
Progress in Inertial Confinement Fusion.
San Francisco, 1-6 February 1978.

LBL-7519

OVERVIEW OF HEAVY ION FUSION PROGRAM IN U.S.A.

Denis Keefe

February 2, 1978

LBL-7519

OVERVIEW OF HEAVY ION FUSION PROGRAM IN U.S.A.[*]

Denis Keefe

February 2, 1978

Lawrence Berkeley Laboratory
University of California
Berkeley, California

1. Present Program and Funding

The funding level in FY1978 for the U.S. national program to study Heavy Ion Fusion is 5 M$. The way this sum can be broken down according to laboratories involved, Department of Energy offices involved, and type of research involved is indicated in summary form in Table I.

Table I - DoE PRESENT FUNDING (FY78)

Laboratories		DoE Offices		Research Categories	
Argonne (ANL)	M$ 1.5	Laser Fusion	M$ 3.5	Accelerator R&D	M$ 3.9
Berkeley (LBL)	1.5	High-Energy/Nuclear	1.4	Targets + Other	1.1
Brookhaven (BNL)	0.9	Basic Energy	0.1	Total	M$ 5.0
Other[†]	1.1	Total	M$ 5.0		
Total	M$ 5.0				
TOTAL = 5.0 M$					
[†] Includes studies of targets, reactor vessel, final beam propagation and ion cross-sections.					

---

[*] This work was supported by the Office of Laser Fusion and the Office of High Energy and Nuclear Physics of the Department of Energy.

The current national program comprises the following major activities:

i) Preliminary design, systems studies, and cost estimates for a reference "pilot-plant" driver [Beam energy = 1 MJ; Beam power on target = 100 TW; specific energy deposition ⩾ 20 MJ/gm.]: Several different reference designs are being pursued which will involve to varying degrees the following accelerator systems:

- rf linac
- synchrotron
- induction linac
- storage rings

ii) Consequent upon this reference design, definition of an intermediate Heavy Ion Demonstration Experiment (HIDE) to test the accelerator technology and to begin to probe the scaling behavior of the heavy-ion target behavior: Current thinking suggests that the beam energy should be about 100 kJ, or roughly one-tenth that of the reference design. In present DoE plans, HIDE is assumed to be operating in FY1985 or FY1986.

iii) Design of targets optimized for heavy-ion driver: Relaxation of the high beam-power requirements would allow accelerator designs to produce lower kinetic energy for the ion and permit a longer final pulse duration, thus easing a difficult demand on present-day accelerator behavior.

iv) Development of a clear understanding of the design implications of the beam space-charge limits, both longitudinal and transverse: Several of the accelerator system design parameters, e.g. apertures, number of final beams, size of final focusing magnets, are sensitive to assumptions about the six-dimensional phase-space density and volume of the beam. Creation and preservation of a suitable density is intimately related to various of the space-charge limits which in turn have an impact on the cost of the driver.

v) Demonstration of suitable heavy-ion sources and acceleration of the beams to modest energies as a bench-test of a pre-accelerator.

vi) Definition of the final focusing procedures including the final beam propagation and stability in a reactor vessel environment.

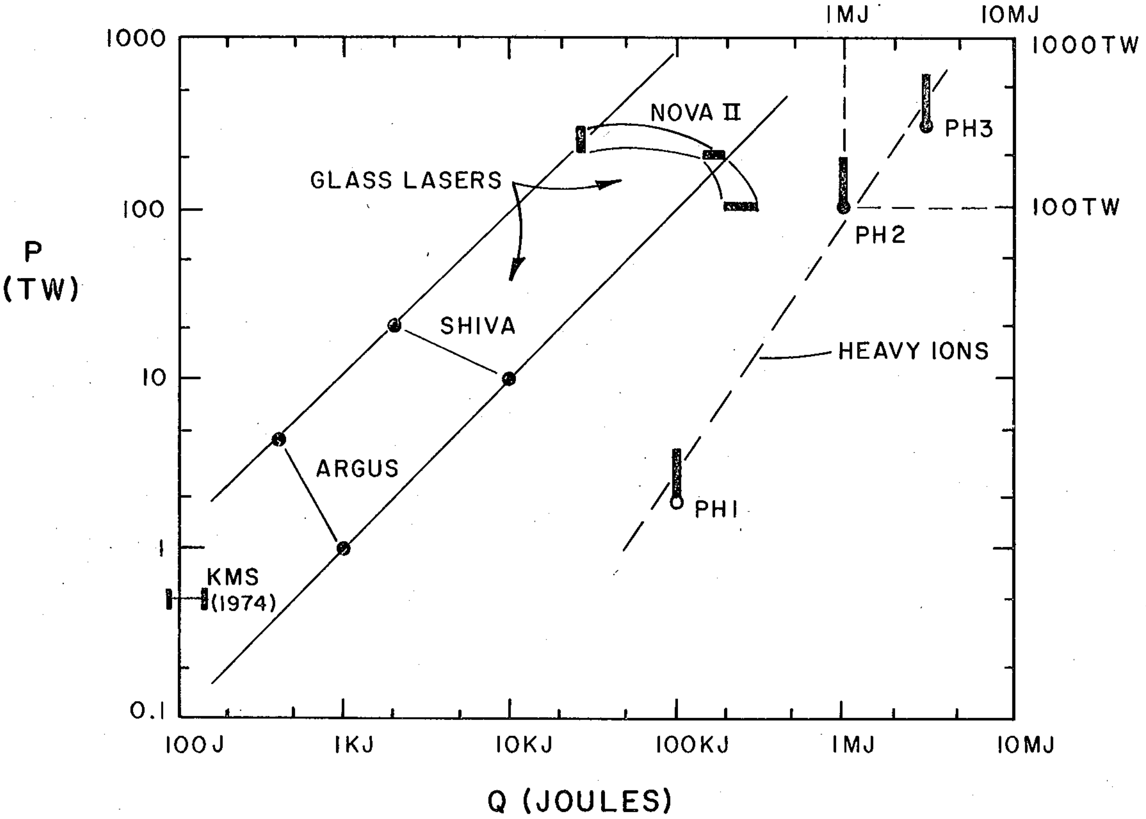
The design strategy of considering first the design of a system with pilot-plant capability and then examining a much scaled-down version to be defined as HIDE (see (i) and (ii) above), can be extended in the other direction. It seems prudent, therefore, to bear in mind during the design the possible extension of the reference example to a multi-megajoule capability. A higher power capability would follow naturally. Table II shows such a possible desirable sequence of steps.

Table II - Heavy-Ion Driver Facility - Three Phases

	Phase I (HIDE)	Phase II ("Pilot")	Phase III (multi-megajoule)
Parameters	100 kJ, 1-10 TW	1 MJ, 100 TW	3 MJ(?), 300 TW(?)
Cost	$\lesssim$ M$ 100	~ M$ 400-500	?
Year	~ 1985	~ 1990	?

2. Characteristics of a Heavy-Ion Driver

The parameter-space to be examined in the design of a heavy-ion driver is very large. For the sake of illustration the range of some parameters is indicated in Table III for the specific example of a 1 MJ, 100 TW, driver that uses "uranium" ions (i.e., mass number > 200) with a charge state no less than $q = +1$ and no greater than $q = +4$. These example parameter ranges are based upon "high-vacuum" design (i.e., no neutralization techniques are invoked), staying with current estimates of the space-charge limits, and using the best estimate (which remains to be confirmed) of realizable beam brightness.



XBL 782-7247

Fig. 1 - An example comparison between glass-laser systems (actual and proposed) and suggested heavy-ion phased facilities. The square (1-10) MJ, (100-1000) TW, is considered the goal for power generation. The vertical bars on the heavy-ion points indicate that the power can be increased, if wished, by doubling the number of final beams. Typically, the heavy ion driver designs have higher energy and less power than the glass laser systems.

Table III - Example Parameter Ranges for 1 MJ, 100 TW Driver

Quantity	Parameter Range
Ion	≈ "uranium"
Charge State	1 - 4
Kinetic Energy	5 - 25 GeV
Range in Heavy Shell	0.1 - 1 gm cm^{-2}
Target Radius	1 - 5 mm
No. of Beam Clusters	≥ 2
No. of Beams/Cluster	1 - 7
Current/Beam	1 - 7 kA

Among the advantages foreseen for a heavy-ion driver are the following: First, the energy deposition profile is relatively uniform; also the energy per particle carried into the target is substantial, ranging from 1/100 to 1/25 of an erg per ion for the examples above. Second, the final beam propagation and focusing in the unfriendly environment of a reactor seem to be tractable and, since the particles have high magnetic rigidity, suitable stand-off distance (10 meters) can be attained. Finally, the suggested accelerator systems are based upon mature technology; the concepts and demonstrations date rather far back in time, e.g., to Wideröe, and Cockcroft and Walton, in the 1920's, to McMillan and Alvarez in the 1940's etc. and there have been continuous engineering developments and improvements achieved over an extended time. The relevance of this experience will be discussed in more detail below. Nevertheless, the basic techniques for achieving some of the novel parameters required for the driver are well in hand but require demonstration before a design can be frozen.

3. Accelerator Systems and Applicability

The many variants of proposed driver systems can be roughly summarized in the form presented in Table IV. The key distinguishing element is to be identified in the column labelled "Voltage Amplifier", namely, the accelerator system used to supply the bulk of the kinetic energy to the ions. These systems usually are rather different in their current-handling capacity: the rf linac may operate with currents of the order 0.1 - 1 amp, the synchrotron with one to two orders of magnitude more, while the induction linac is most useful in the kiloampere range. The rf linac system employs a number of storage rings in which many turns are accumulated, then rapidly bunched and ejected to the target. The synchrotron system likewise might employ several storage rings for current amplification; as few as one is not entirely ruled out. Both the rf linac and synchrotron employ tuned resonant radio-frequency systems to accelerate the particles. In the case of the induction linac, current compression of a single long bunch of charge is accomplished by the slight ramping of the pulsed voltages along its length and the beam can be split at the end into a number of channels for transport to the target, without the use of storage rings. The induction cavities are non-resonant and are driven by pulse-power modulators.

The injectors for all of these systems will involve higher currents at lower ion-speeds than are in common use today. High current, as such, is not a problem (for example, 9 amps of Xe ions was obtained in a recent test with a CTR multiaperture source), but careful attention to detail is required to scale from the usual few-milliampere sources now running to the 25 - 100 mA ones required, in order to preserve the high-brightness features to the utmost degree. The early (low-velocity) part of the rf linac can be scaled directly in size and downward in frequency from existing Wideröe structures. The induction linac presents a special case in that its injector can rely on the rf linac/low-energy accumulator technology or employ an unconventional type of non-resonant drift-tube structure based upon pulse-power technology. The latter would provide a more attractive match to the induction linac, and a small system is being modelled at Berkeley to test the concept.

Table IV - ACCELERATOR SYSTEMS - FOR DRIVER

SOURCE	INJECTOR	VOLTAGE AMPLIFIER	CURRENT AMPLIFIER
PLASMA	RF LINAC WIDERÖE)	RF LINAC$^{(a)}$ (ALVAREZ) SYNCHROTRON$^{(b)}$	ACCUMULATOR RINGS WHICH INCLUDE RF BUNCHING AND/OR INDUCTION LINAC BUNCHING
PLASMA	RF LINAC 1 GeV ACCUMULATOR	INDUCTION LINAC$^{(c)}$	PULSE COMPRESSED BY RAMPED VOLTAGES IN ACCELERATOR
	or		
PLASMA (CTR) OR CONTACT IONIZATION	100 MeV PULSED DRIFT TUBE ACCELERATOR ~50 AMPS		NO ACCUMULATORS

(a), (b), (c): TYPICAL PEAK CURRENT CAPABILITY: (a) 0.1 - 1 amp
(b) 1 - 100 amp
(c) 100 - 10,000 amp

An important consideration for circular machines in which the particles remain bunched for many revolutions is the beam loss due to ion-ion collisions (within a bunch) of the charge-exchange type:

$$A^{+1} + A^{+1} \rightarrow A^{0} + A^{+2}$$

The reaction rate for this process has a bearing on the synchrotron repetition rate and cost; more work on many kinds of ions and a number of higher charge states is needed to establish the optimum ion choice and the degree of beam loss.

Earlier it was remarked that the accelerator technology-base is a mature one. Apart from maturity many of the achievements and much of the experience is highly relevant to the needs of a suitable driver. For example:

a) Adequate <u>repetition rate</u> (1 - 10 Hz, or more) is a normal by-product of conventional accelerator design.

b) <u>Electrical efficiency</u> from electric mains to the beam in the 10% to 25% range should be readily achievable. Efficiency has not usually been a design consideration for research accelerators; nonetheless, the Stanford Linear Accelerator runs at 3-4% efficiency, the Los Alamos proton linac has 16% efficiency, the JINR (Dubna) 30 MeV induction linac (under construction) will be 15% efficient, while the PEP 6 MW cw rf system is believed to have an overall efficiency of 42%.

c) <u>Operating and control experience for high availability.</u> Even a dozen years ago several research accelerators averaged 95% availability. Adequate beam diagnostics and computer control has involved considerable learning experience in the last 10-15 years but today has reached a level of sophistication far beyond what will be needed for a single-purpose dedicated driver.

d) Current concepts for an accelerator driver involve the use of several kilometers (5-8) of technical components including transport lines to the target. The configuration could range from circular, to almost entirely linear, or to folded linear, depending on site requirements. An integrated length of several kilometers of technical components seems inevitable not just for accelerator systems but also for E-beam and laser systems. (Nova II, for example, albeit with a goal and parameters different from that of the accelerator systems under discussion, will have an integrated component length in the range 2.5-3 km). The physics design and engineering approaches to accelerator construction have undergone considerable evolution in the process of building several large facilities (See Table V) in the past fifteen years. If one includes sophisticated secondary beam

Table V: Major Accelerator Facilities of the Last 15 Years

Location or Title	Particle	Accelerator Type	Energy (GeV)	Length of Technical Components
Operating:				
SLAC (U.S.)	electron	linac	20	3 km
LAMPF(U.S.)	proton	linac	1	1 km
FNAL (U.S.)	proton	synchrotron	500	6 km +
SPS (Switz.)	proton	synchrotron	400	6 km +
ISR (Switz.)	proton	storage rings	2 x 30	2 x 1 = 2 km
Under Construction:				
PETRA (W. Germany)	electron	storage ring	19	2 km
PEP (U.S.)	electron	storage ring	18	2 km
ISA (U.S.)	proton	superconducting storage rings	2 x 400	2 x 4 = 8 km
FNAL Doubler (U.S.)	proton	synchrotron	1000	6 km

transport lines the integrated structure length brought into operation in the past fifteen years is roughly 30 km - a number which will double in the next eight or so years. The importance of this construction experience is in the learning process of where big savings on large-scale systems can be safely made, and conversely, where one ought not to cut too many corners. While this experience is of general relevance, there is need, however, for some caution and considered design and engineering in scaling up heavy-ion and induction linac systems from their present subkilometer scale. Only two heavy-ion rf linacs are in operation (SuperHILAC at Berkeley and UNILAC at Darmstadt); a third is under construction (GANIL) in France. Only one heavy-ion synchrotron is operating (Bevalac at Berkeley) although construction of others are under consideration in West Germany and the U.S.S.R. Several induction linacs have been operated long and successfully with kiloampere electron-beams but all have been on a relatively small laboratory scale. Thus there is a vital need for good conceptual-design and systems-studies to understand how best to achieve cost-optimization for significant scaling of these systems. Such studies are underway at each of the accelerator laboratories involved.

e) Multimegajoule beams have been routinely used. The ISR, FNAL, and SPS facilities all operate with stored energy in the beams of up to 3 MJ, or so. Only certain features of this experience, however are relevant (beam dumping and beam abort procedures). The relativistic factor, γ = Total energy/Rest energy, is very large for these proton beams and the space charge limits can be obeyed with reasonable transport systems. The low value of γ required for heavy ions in a driver system ($\lesssim 1.1$) results in a new need to understand more precisely the generation, propagation and stability of space-charge dominated low-velocity beams. Related studies are being actively pursued at the accelerator laboratories involved in the heavy-ion fusion program. It is, incidentally, worth remarking that the stored beam charge in the CERN ISR ($\approx$ 100 μC) is approximately that needed for a heavy ion driver beam.

4. Laboratory Programs

Details of these programs can be found in the mid-year and year-end reports published by the Argonne National Laboratory, Brookhaven National Laboratory and the Lawrence Berkeley Laboratory. Two other good sources of technical information are the Proceedings of Workshops on Heavy Ion Fusion, one held at Oakland in July 1976 (available as LBL report 5543) and the other at Brookhaven in October 1977 (soon to be published as a BNL report). Thus the laboratory programs will be referred to here only in the briefest manner. The preceding sections of this discussion have centered around identification of the two areas requiring more complete study and definition: (i) Good conceptual design and systems studies to allow optimization of individual designs and intercomparison among the alternatives; and (ii) demonstrating the production of the high-current heavy-ion beams needed and achieving preservation of adequate brightness under early acceleration conditions. All aspects of these two major areas are naturally receiving attention at all three accelerator laboratories but with varying degrees of emphasis. At the request of the Department of Energy, short-term studies on costs have been apportioned as follows: full-energy rf-linac systems at BNL, synchrotron systems at ANL, induction linac systems (includes low energy rf + accumulator injector) at LBL. High-current source development is underway at ANL (in collaboration wtih Hughes Research Laboratories), and at LBL where a multiaperture CTR design has been developed. Following achievement of a suitable source, acceleration through a high voltage column will be explored at 1.5-2 MV at ANL and at 0.75 MV at LBL, to determine the degree of emittance modification. Individual prototype subsystems applicable to low-velocity rf accelerators are being fabricated at ANL amd BNL, whereas at LBL designs based upon the existing SuperHILAC and its imminent upgraded version involving Wideröe structures, are being developed for lower frequency application. A large (1000 cm^2) contact ionization pulsed high-voltage (500 kV) source is being built at LBL to serve two purposes; first, to allow demonstration of pulse-power drift-tube acceleration for a few stages; and second, to allow high-current beam-propagation studies through a long periodic magnetic focussing system to establish a connection between experiment and theory in the matter of beam instabilities and transverse space-charge limits. Experiments on the degree to which "high-vacuum" space-charge limits can be violated are in progress at BNL, where the conventional limit was exceeded by a factor of 7 or 8 for several turns of a bunched proton beam in the AGS. Another experiment uses electrons injected to create space-charge neutralization in a bunched beam - a technique which, if it works reliably, will allow considerable relief in some of the difficulties in the final focussing system.